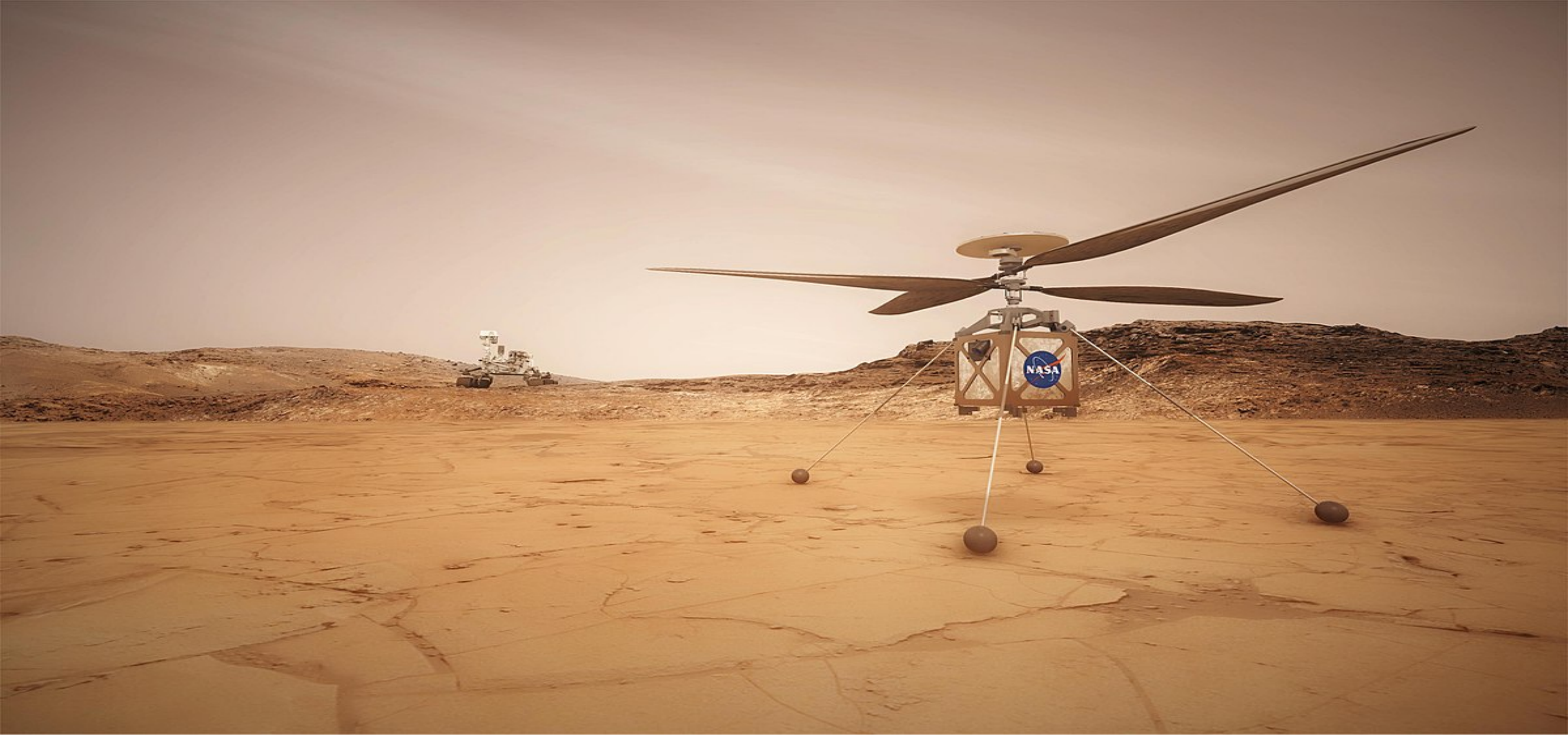


Rover Localization in Mars Helicopter-generated Aerial Maps: Experimental Results in a Mars-analogue Environment

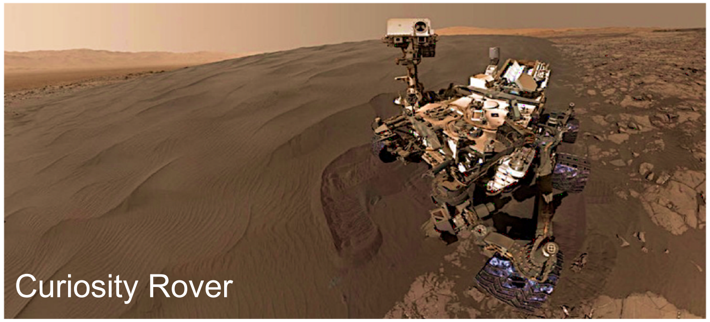
Kamak Ebadi, Ali-Akbar Agha-Mohammadi

ISER 2018

Jet Propulsion Laboratory
California Institute of Technology

Introduction

Current



Curiosity Rover

Science-oriented mission

- Understanding Mars geology and habitability of environment
- Frequent stops for scientific interests

Day-to-day operations

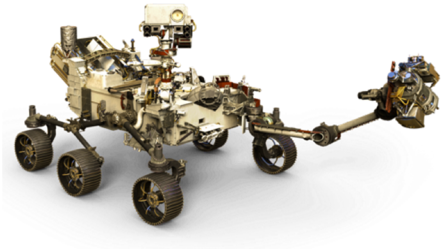
- Planning tactical activities for 1-3 Martian days in a single ground-in-the-loop cycle
- "Restricted sols" due to Earth-Mars time gap

Limited use of AutoNav

- Significantly slower than manual drive
- Wheel damage (MSL)

Future (2020 and beyond)

Mars 2020



Mars Sample Return Fetch rover (concept)

More drive-oriented missions

- e.g., Collect sample tubes and return to the base before to launch to Earth
- Travel longer distance per sol

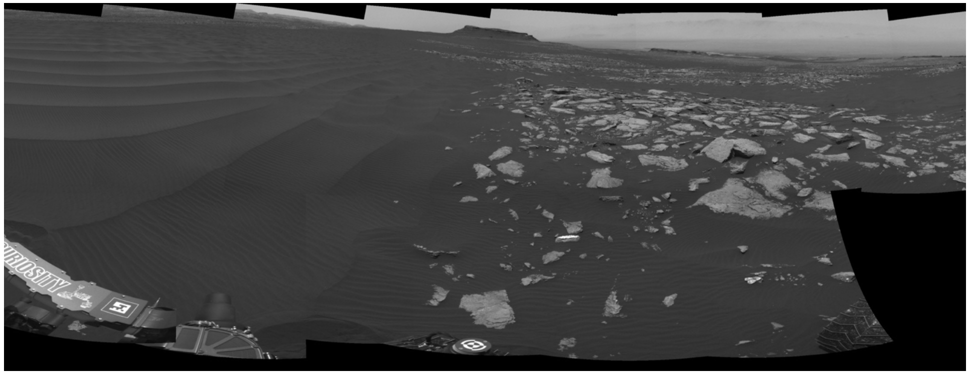
Higher dedication to AutoNav

- Drive beyond the line of sight
- Drive longer on restricted sols

Increased onboard resources

- Vision-dedicated processors (Mars 2020) and multi-core general-purpose processors (future missions)

Autonomous Vision-based Navigation



Feature-poor terrain on Mars
(Left: MSL Curiosity, Right: MER Opportunity)

Challenges:

- Failure to detect features on low texture terrain
- Failure to track features due to glare or shadows

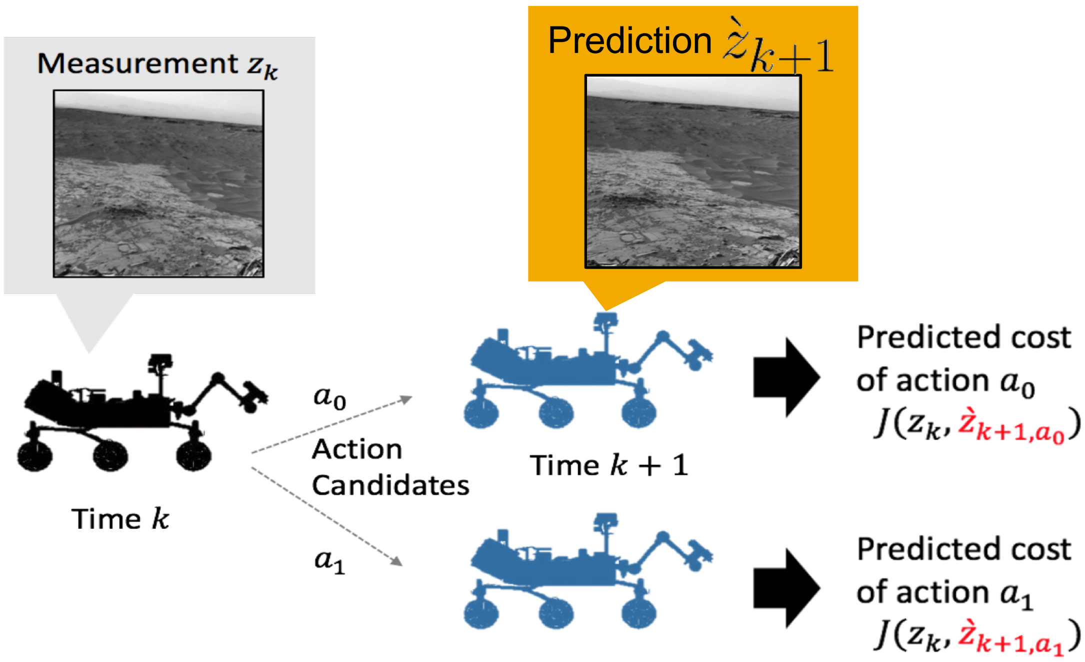
Current Solution:

- Human intervention (manual mast pointing)

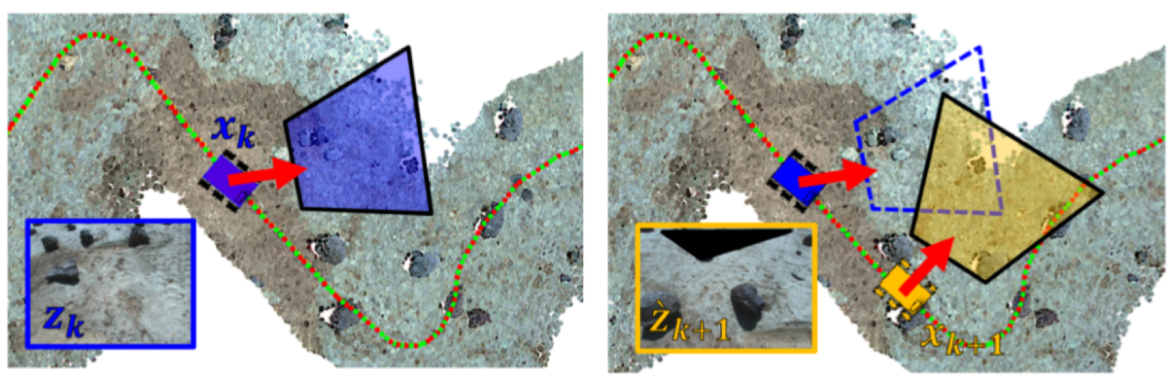
Alternative Solution:

- perception-aware mast pointing to reduce uncertainty and visual odometry failure

Perception-aware Mast Pointing

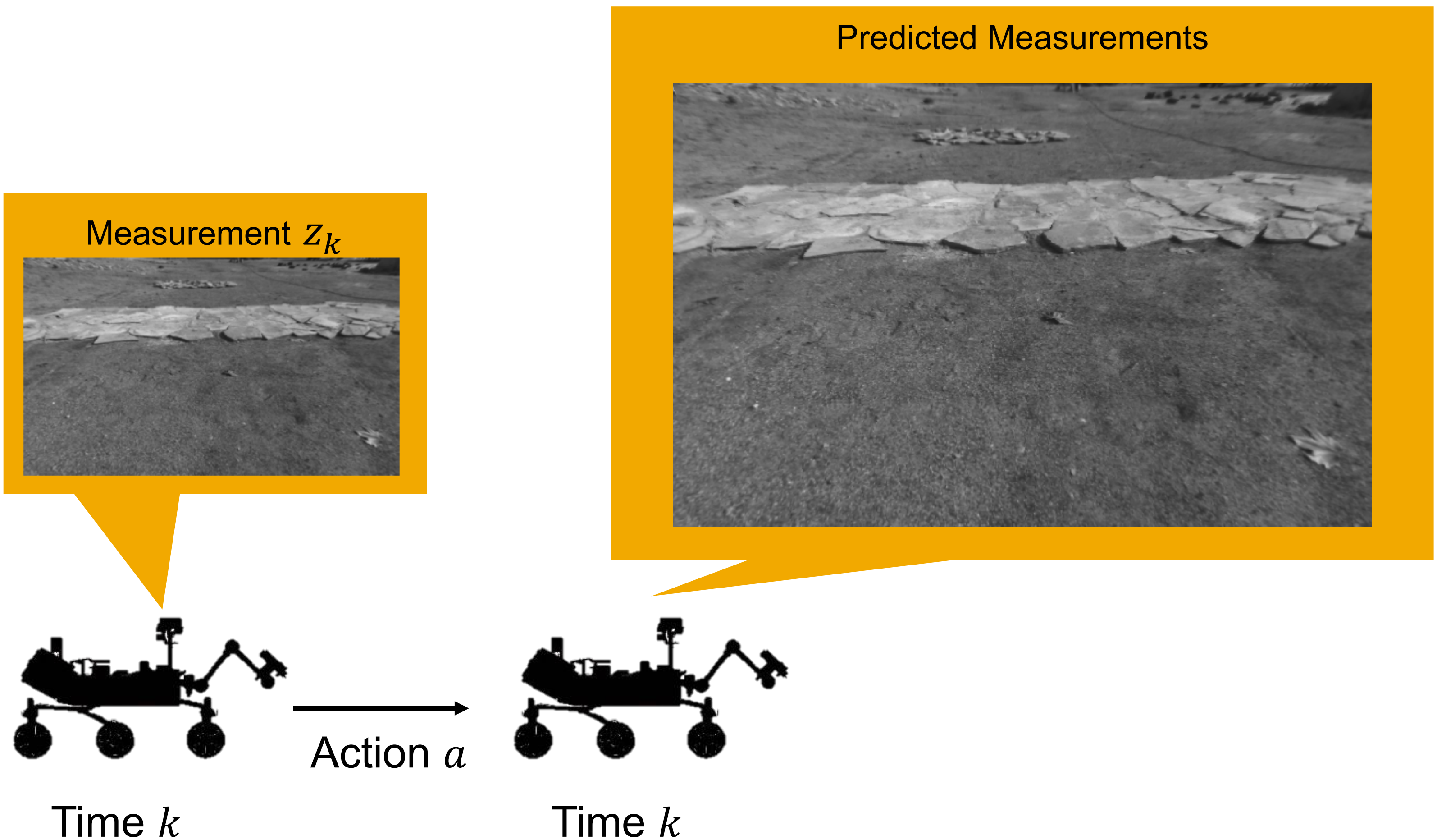


$$J(\grave{z}_k, \grave{z}_{k+1}) = \|\Delta \grave{x}_{k,k+1} - \Delta x_{k,k+1}\|$$

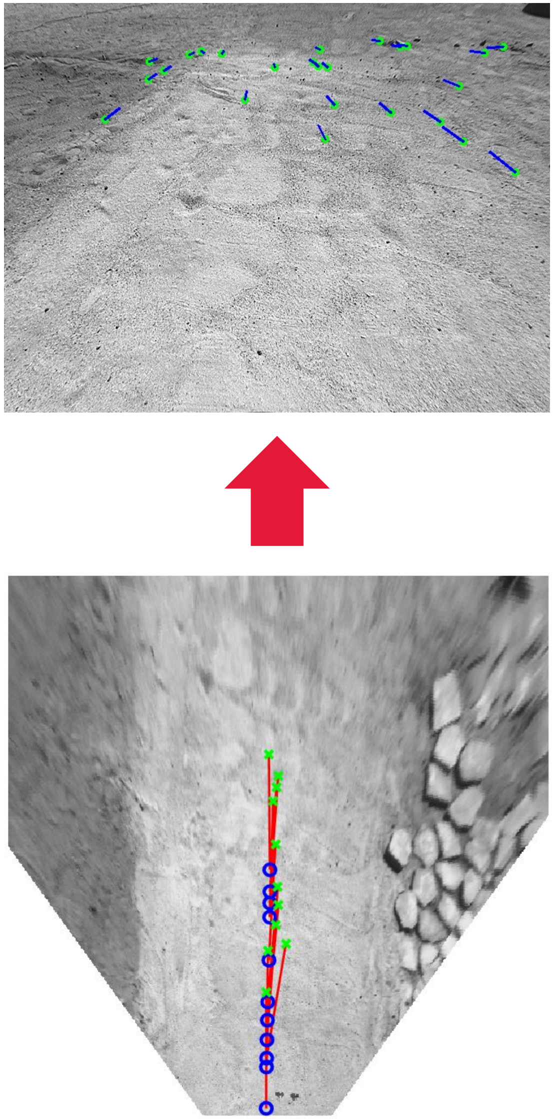


Perception-aware Mast Pointing

Example of Synthesized Images



Perception-aware Mast Pointing



Passive

Perception-aware

Perception aware mast pointing

Pros:

- Reduce uncertainty and visual odometry failure

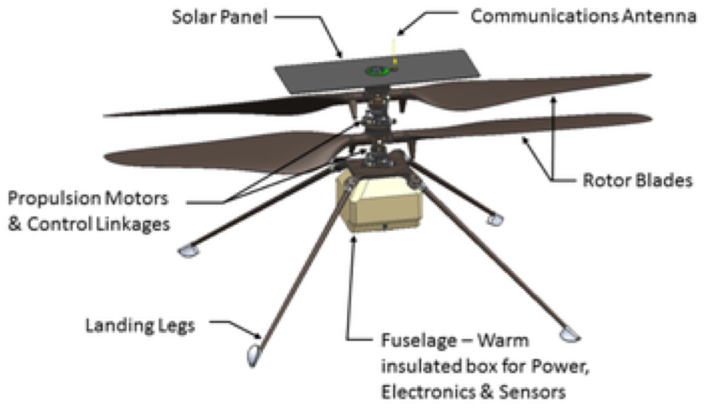
Cons:

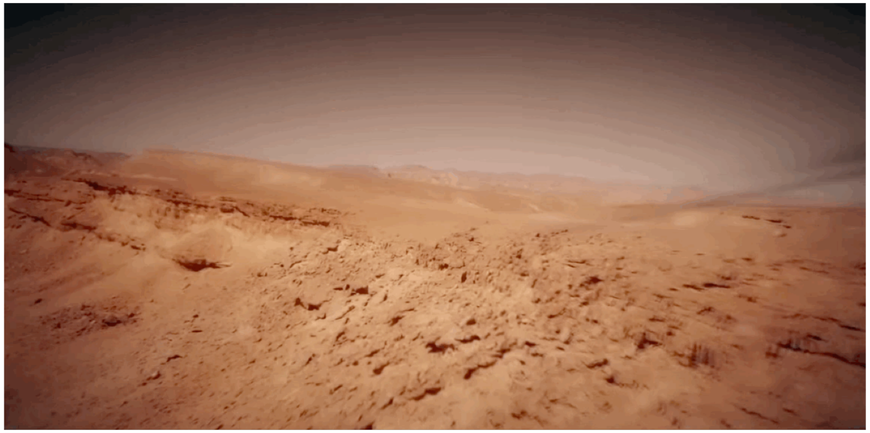
- Relies on rover’s measurement of the local terrain
- Can only predict few steps into the future
- Not suitable for strategic long term planning

A Potential Future Solution → Mars Helicopter!

- Rely on high resolution aerial imagery for long term trajectory and mast planning

Mars Helicopter

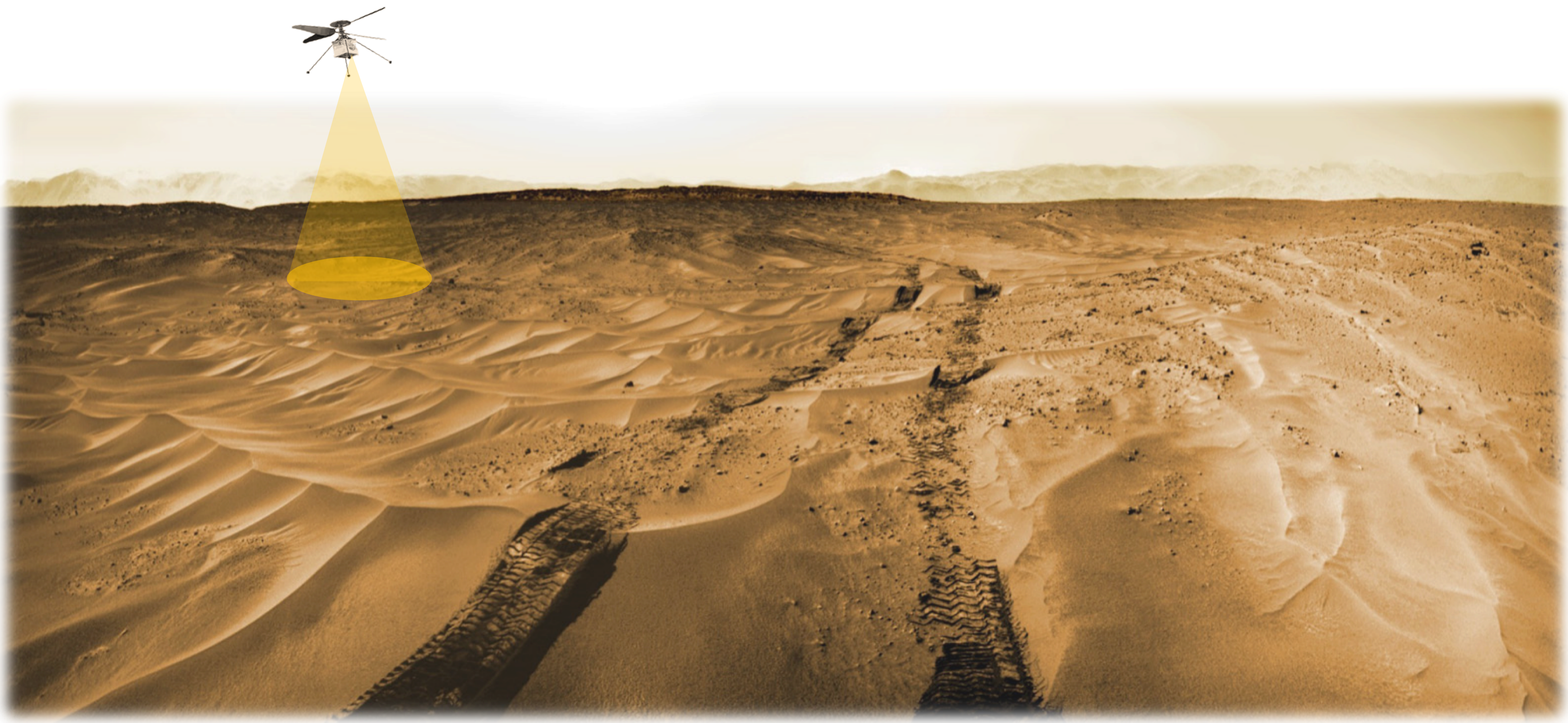




Specifications:

- Flight Time: 90s/sol
- Flight Range: ~600m
- Flight Altitude: 3m to 10m

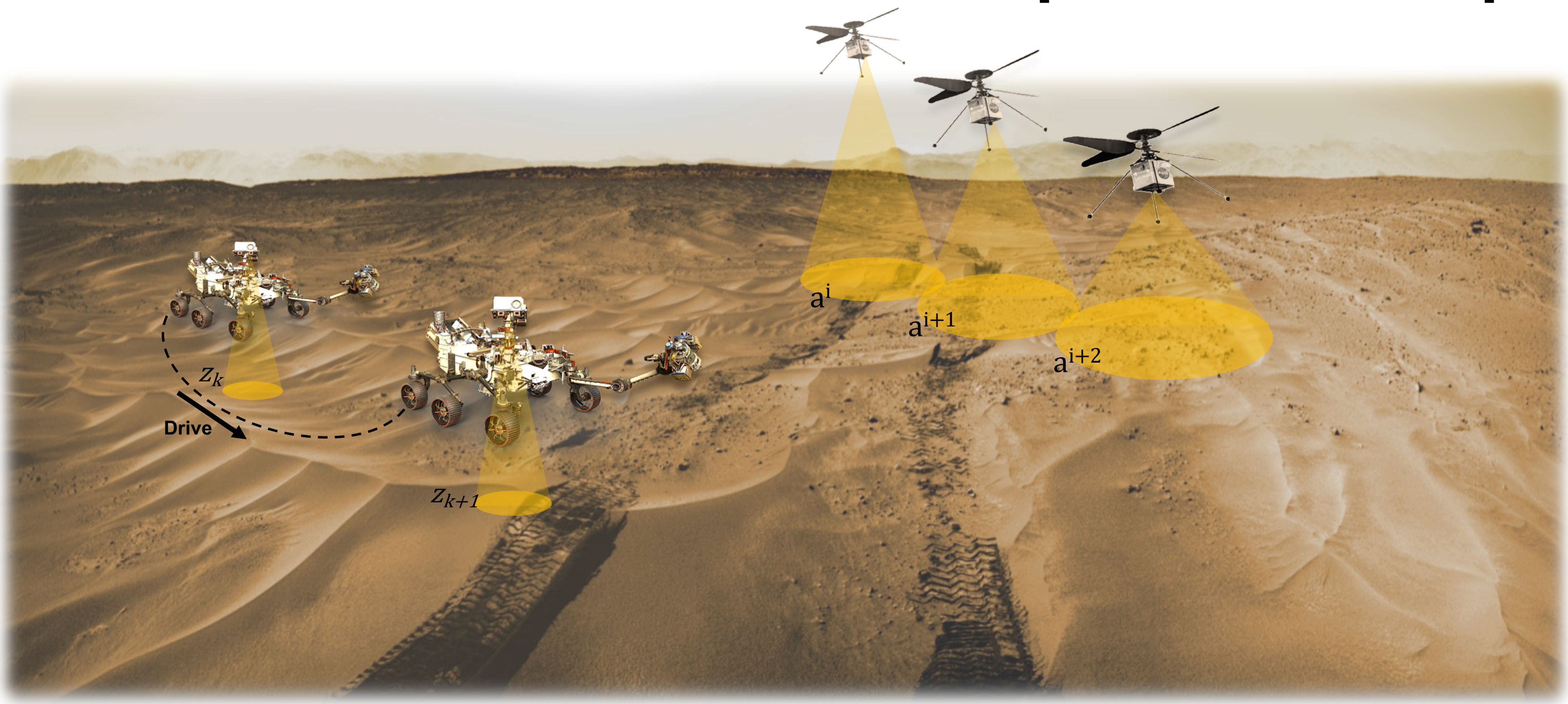
Mars Helicopter – Scouting the Martian Terrain



Objective:

- Identification of interesting science targets
- Acquire high resolution aerial imagery of the environment

Rover Localization in Mars Helicopter Aerial Maps



Objective:

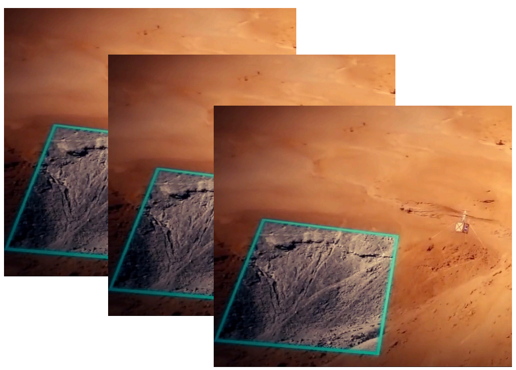
To create a high resolution aerial map that can be used for rover's long term strategic planning

Challenge:

Rover needs to establish its pose in the provided aerial map for a successful perception aware trajectory and mast planning

Aerial-to-Ground Localization

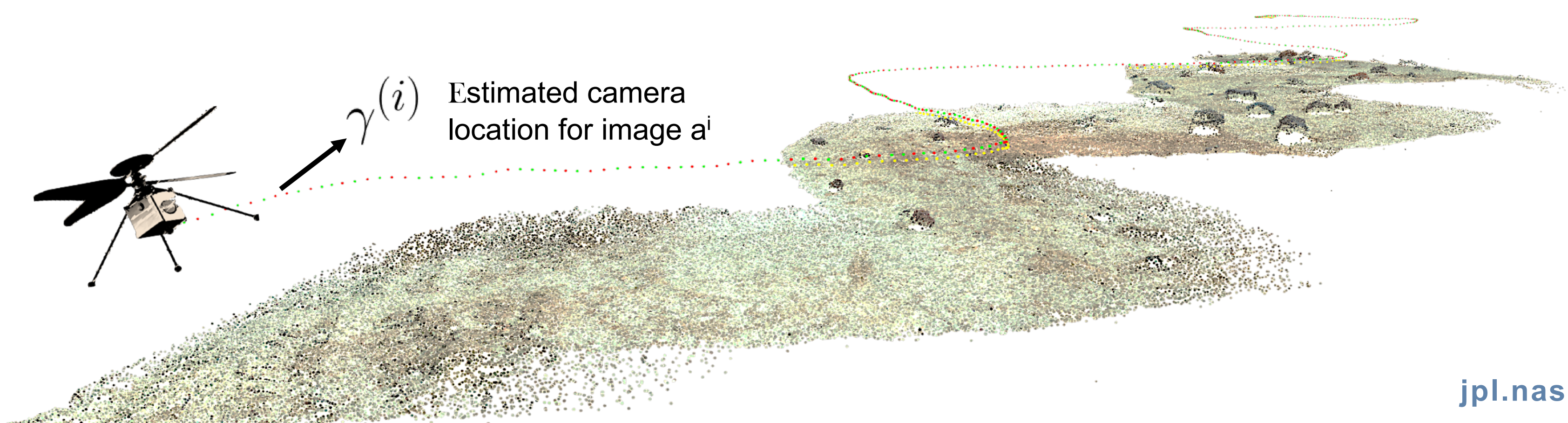
CGM : Copter-generated Map



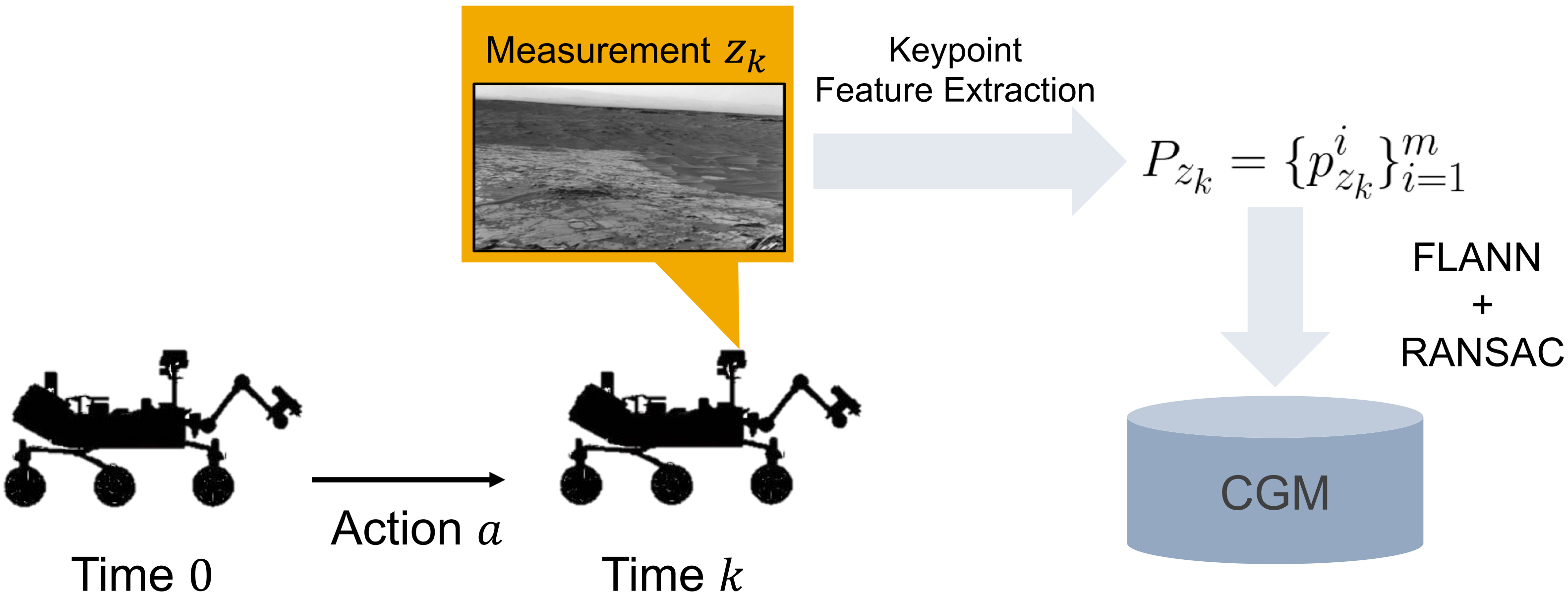
Sequence of Aerial Imagery $A = \{a^i\}_{i=1}^n$

- Image feature extraction and matching
- Camera pose estimation
- Recovery of the 3D structure of the terrain

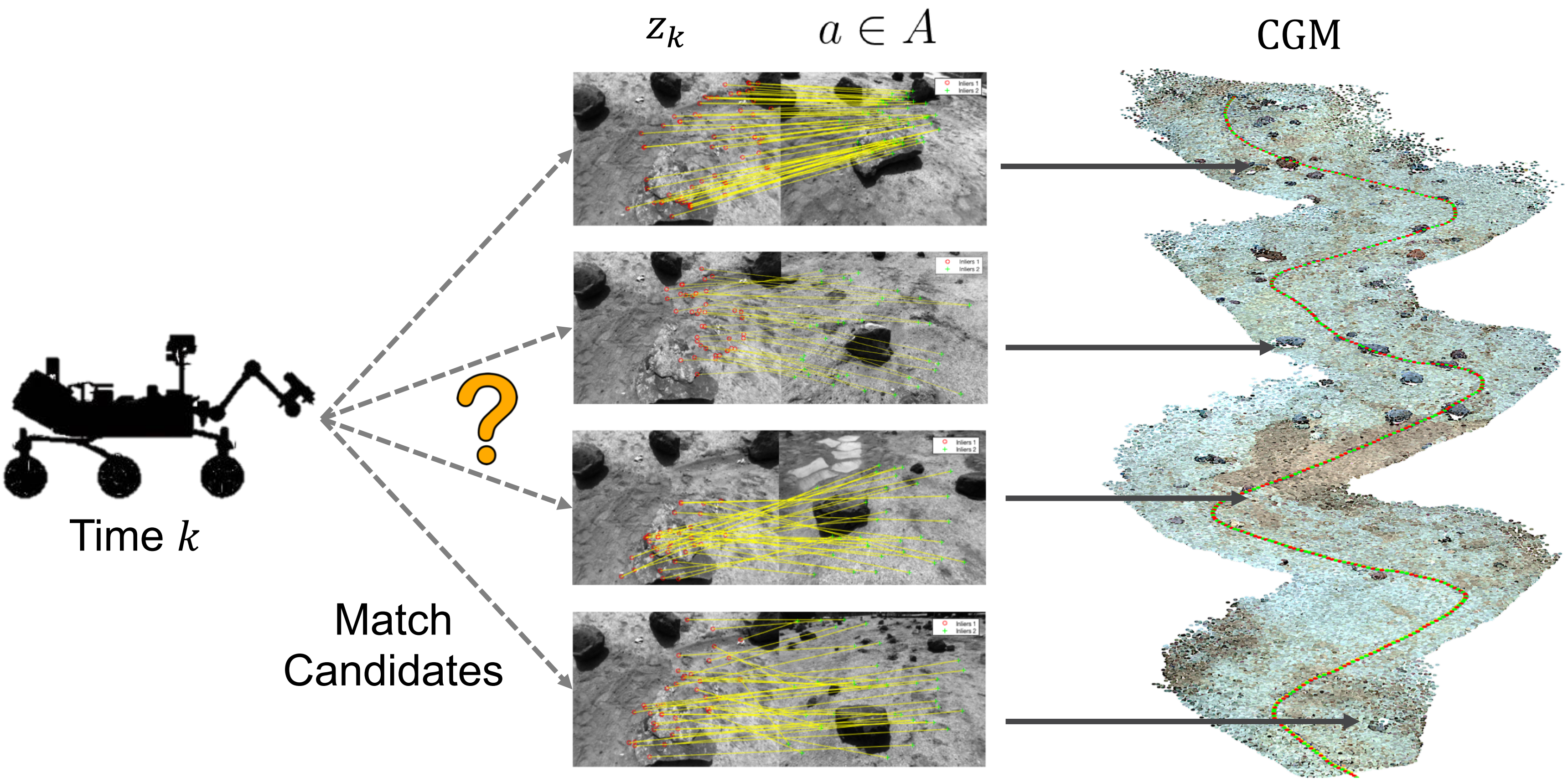
CGM



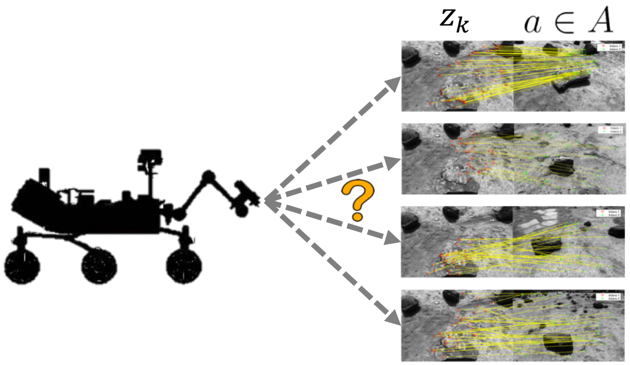
A2G Image Matching

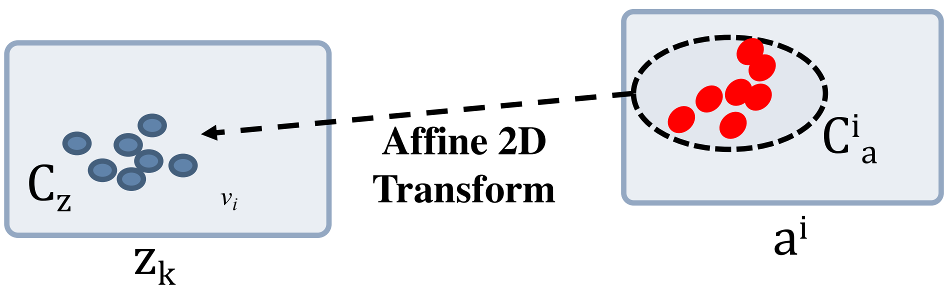


Ambiguity in Data Association



A2G Image Similarity Evaluation



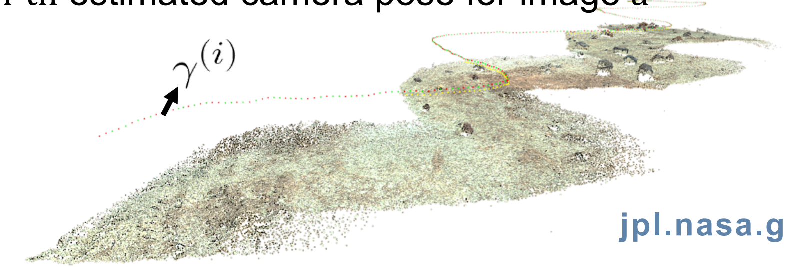


$$R(C_a, C'_z) = |C_a|^{-1} \sum_{j=1}^{|C_a|} ||c_a^j - c_z'^j||$$

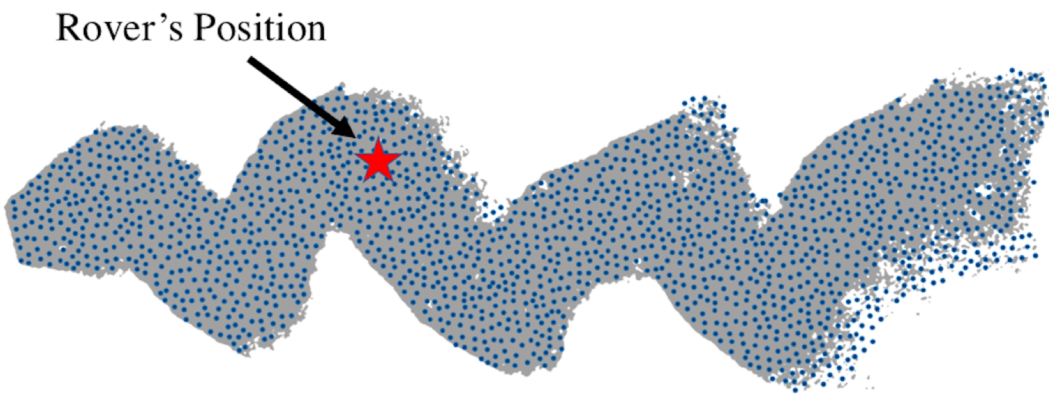
$$s(z_k, a^i) = (1 + R(C_a^i, C'_{z_k}))^{-1}$$

$$p(z_k|\gamma^{(i)}) = s(z_k, a^i)(\sum_{a \in A} s(z_k, a))^{-1}$$

i-th estimated camera pose for image a^i

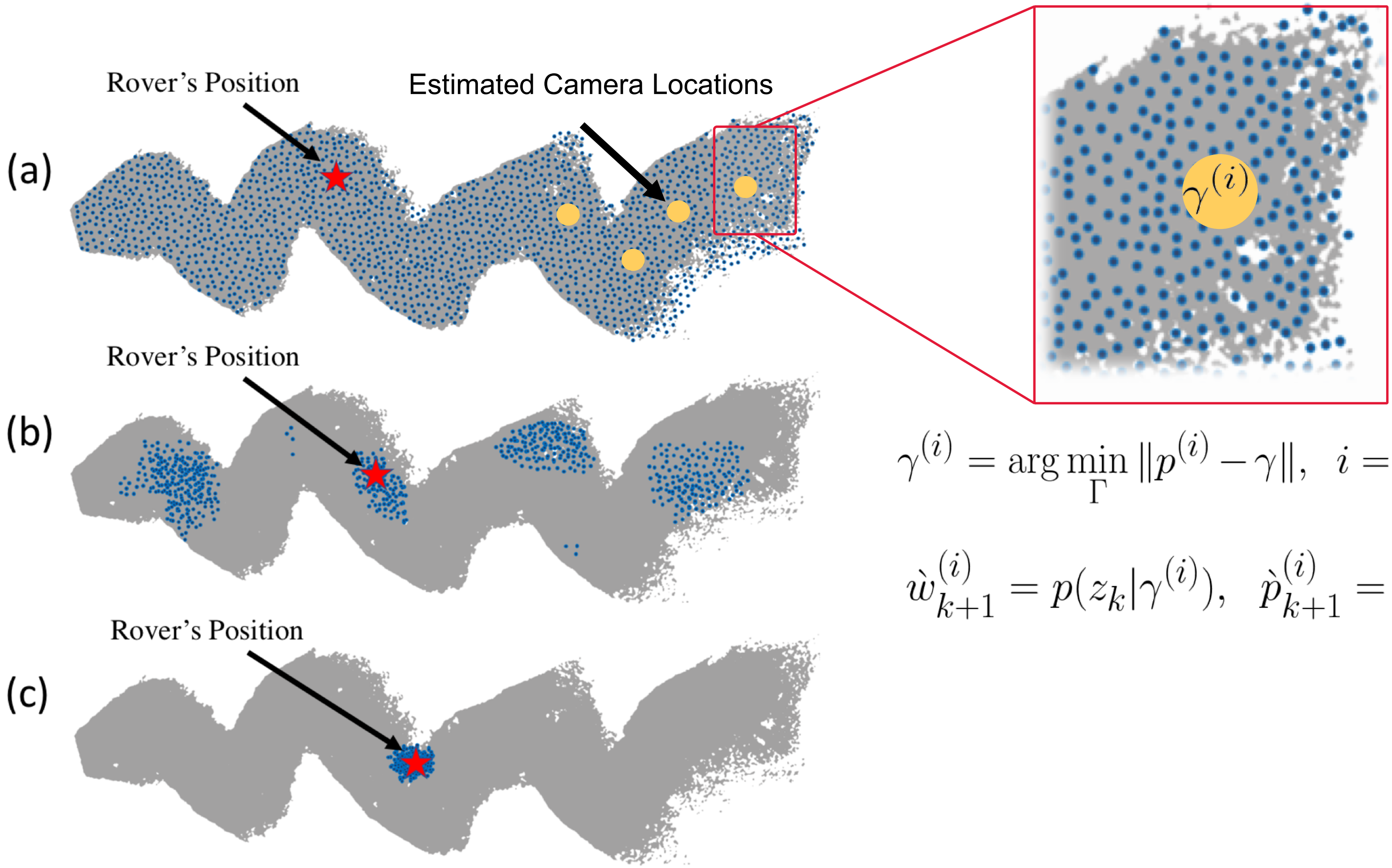


Particle Filter Localization



- $b_k = p(x_k | z_{0:k})$
- $b_k(x) = \sum_{i=1}^{n} w_k^{(i)} \delta(x - p_k^{(i)})$
- $s_k = (p_k^{(i)}, w_k^{(i)})_{(i=1:n)}$

Particle Filter Localization

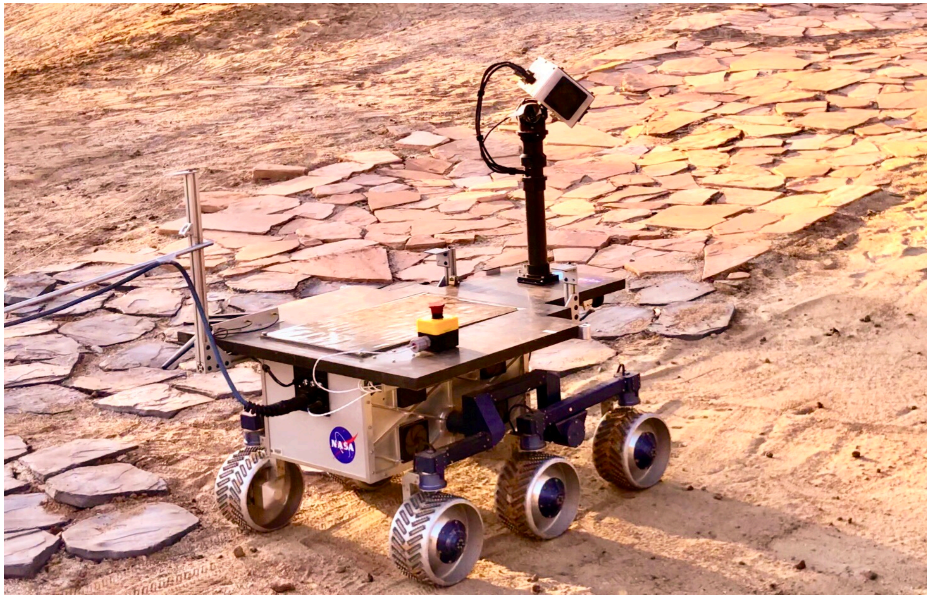


$$\gamma^{(i)} = \arg\min_{\Gamma} \|p^{(i)} - \gamma\|, \quad i = 1 \cdots n$$

$$\grave{w}^{(i)}_{k+1} = p(z_k|\gamma^{(i)}), \quad \grave{p}^{(i)}_{k+1} = p^{(i)-}_{k+1}$$

Experiments

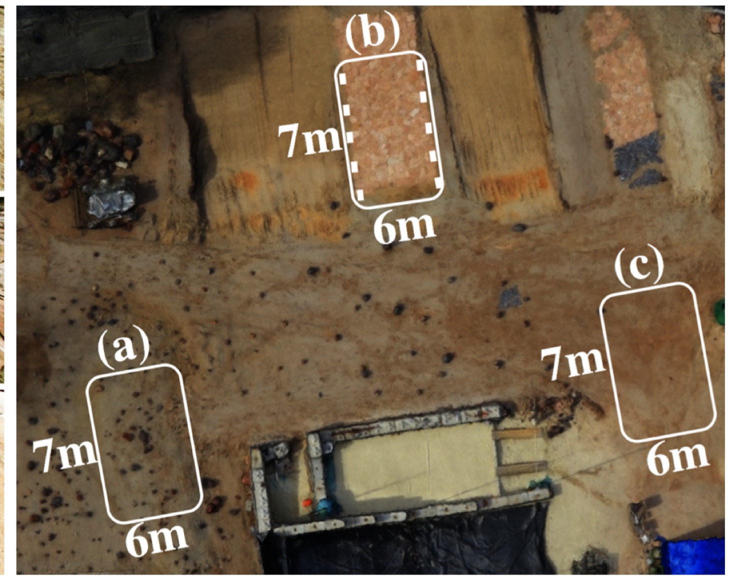
Jet Propulsion Laboratory's Mars Yard



- Outdoor simulated Mars-analogue environment
- Large test area to test different robotic applications
- Various natural lighting conditions, soil characteristics, and rock colors.

Experiments

Jet Propulsion Laboratory's Mars Yard

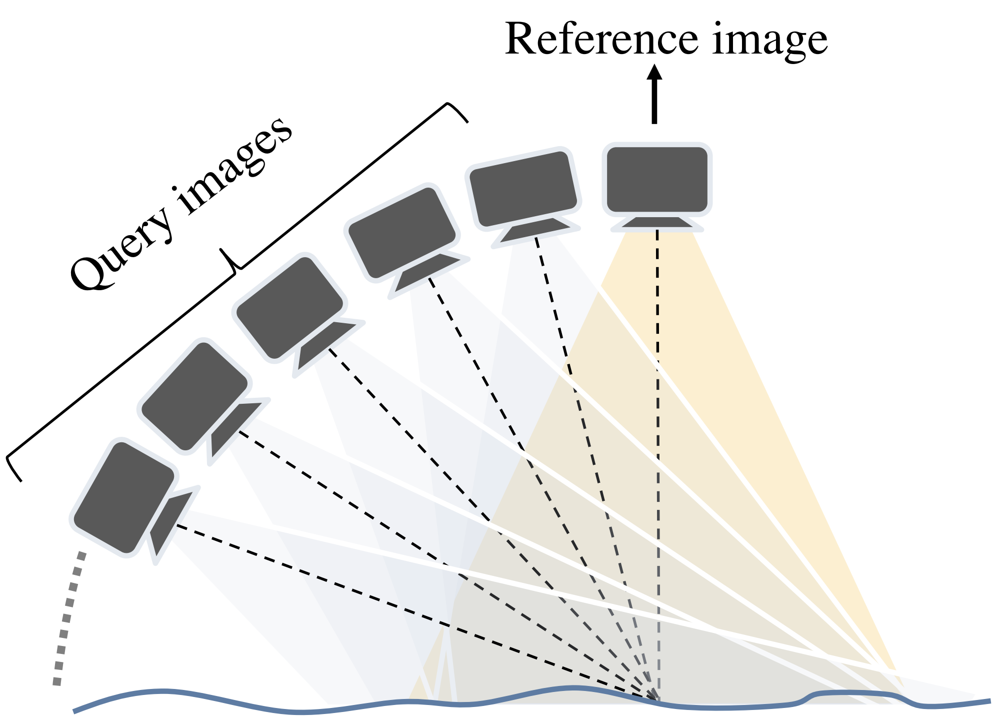


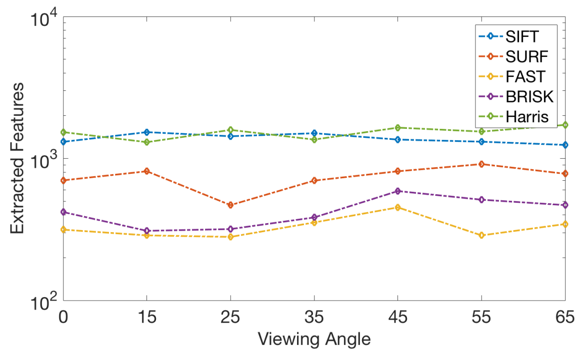
a) Feature-rich terrain

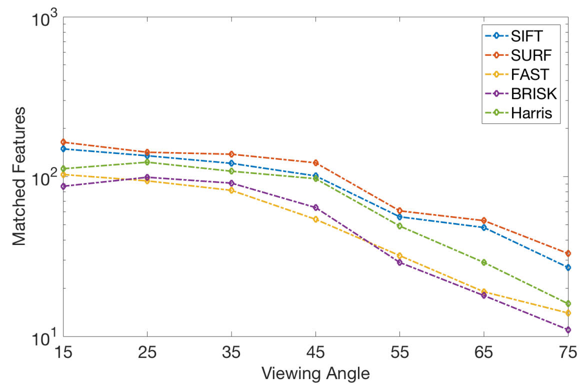
b) Repetitive and ambiguous features

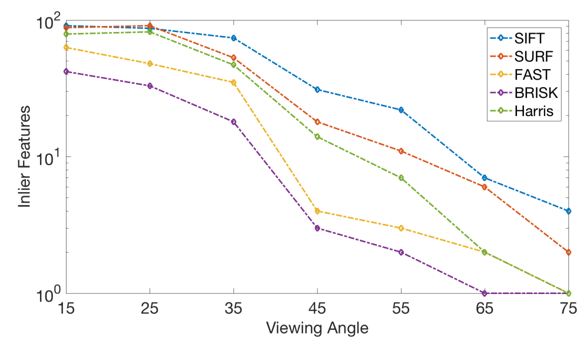
c) Feature-poor terrain with sparse landmarks

Viewing Angle Variations

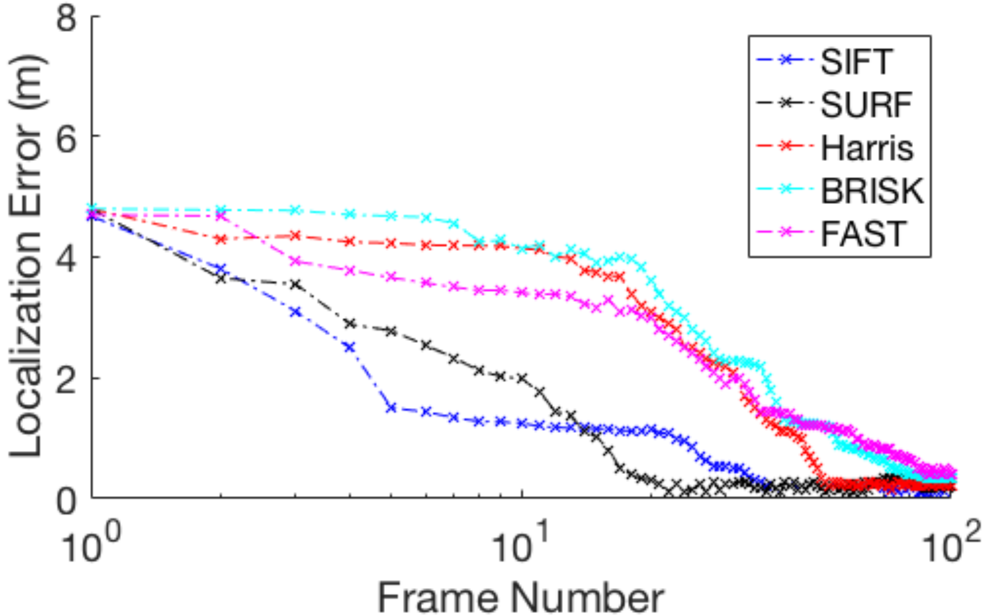






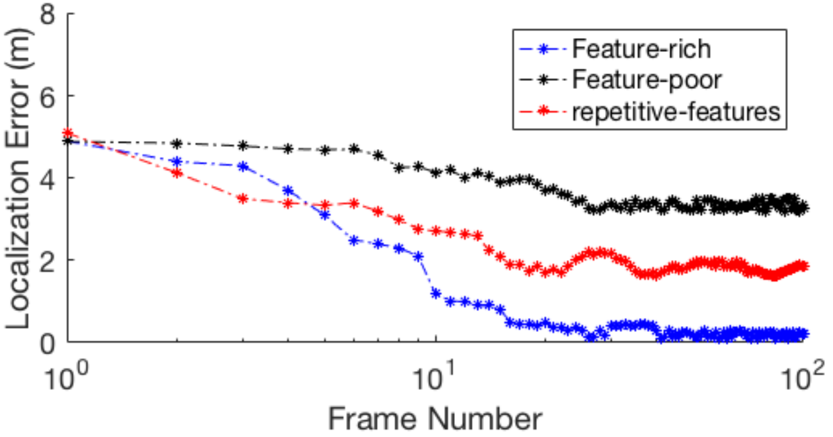


Comparison of Different Feature Detection/Description Methods



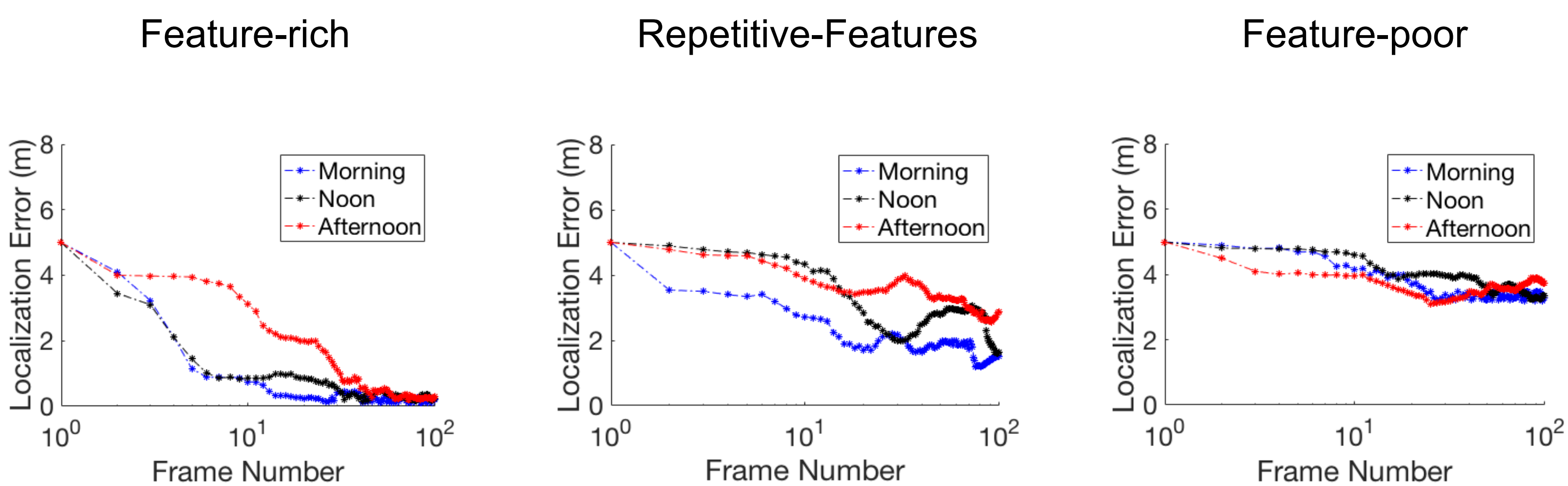
- Terrain Type: Feature-rich
- Time of Day: Morning for both Aerial and Ground imagery
- Performance Metric: Localization accuracy compared to rover’s ground truth

Terrain Type Variations



- Terrain Types:
  - Feature-rich,
  - Feature-poor
  - Repetitive and Ambiguous Features
- Time of Day: Morning for both Aerial and Ground imagery
- Performance Metric: Localization accuracy compared to rover’s ground truth

Illumination Variations

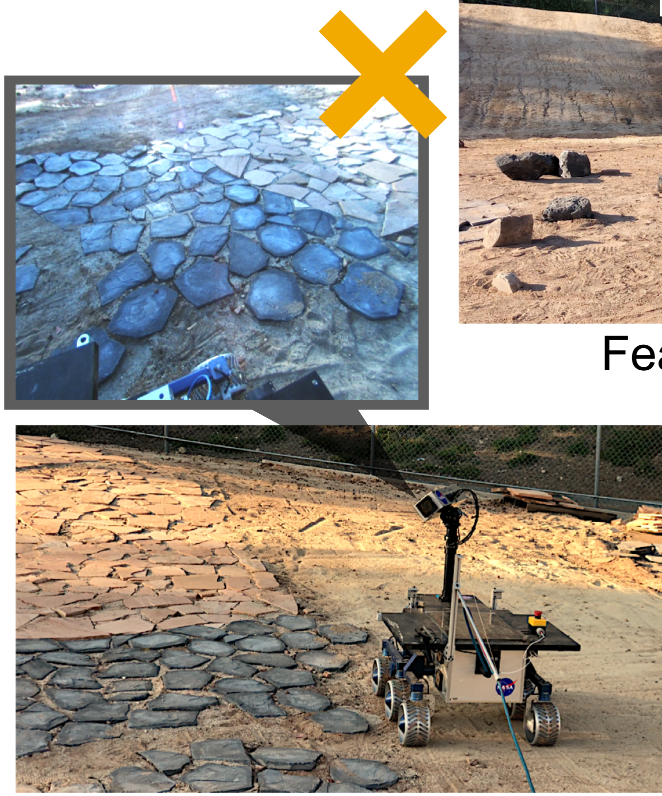


- Aerial Dataset obtained at 9:00AM
- Ground imagery obtained:
  - Morning (9:00 AM)
  - Noon (1:00 PM)
  - Evening (5:00PM)
- Terrain Types:
  - Feature-rich,
  - Feature-poor,
  - Repetitive Features

Conclusion

➢Robust A2G localization is possible in a feature-rich Mars-like environment

Feature-rich Terrain

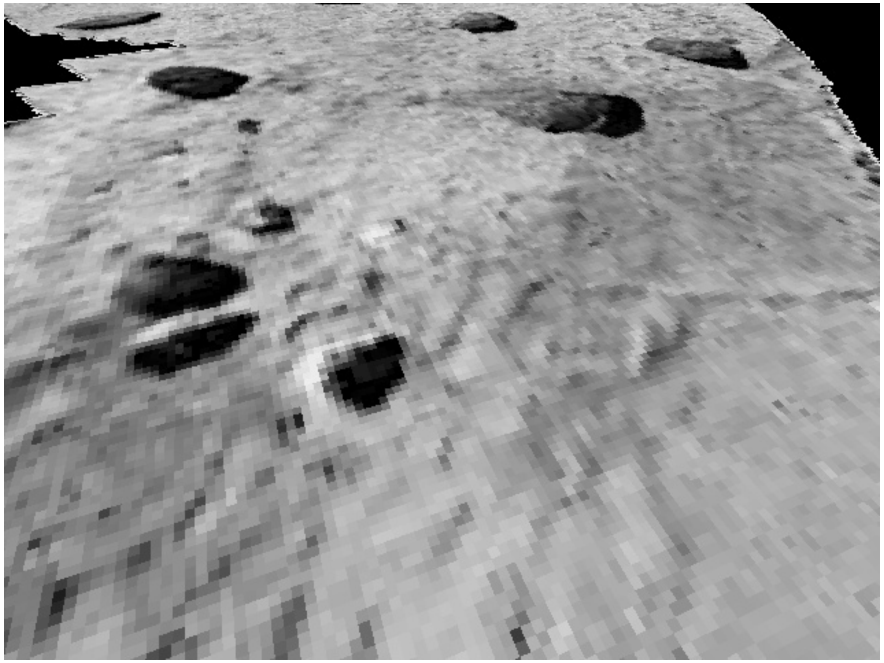


Repetitive Features Terrain

Feature-poor Terrain

Conclusion

- Once the rover is localized in the map → long term strategic planning

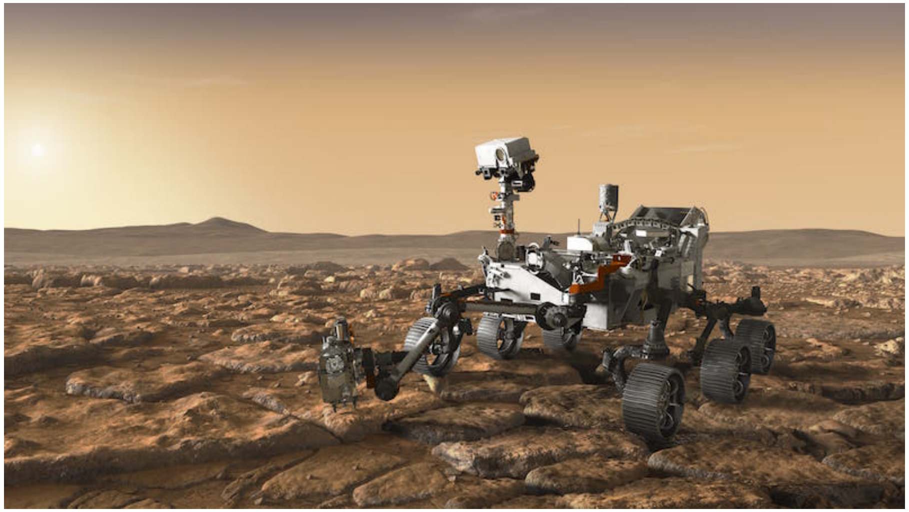


Future Work

Distributed Collaborative Mapping

- Investigate the graph-based methods for distributed collaborative mapping using a team of rover and helicopter in a Mars-like environment.

Acknowledgement



The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Rover Localization in Mars Helicopter Aerial Maps: Experimental Results in a Mars-analogue Environment

Kamak Ebadi, Ali-Akbar Agha-Mohammadi
Contact: Ebadi@jpl.nasa.gov

Jet Propulsion Laboratory
California Institute of Technology

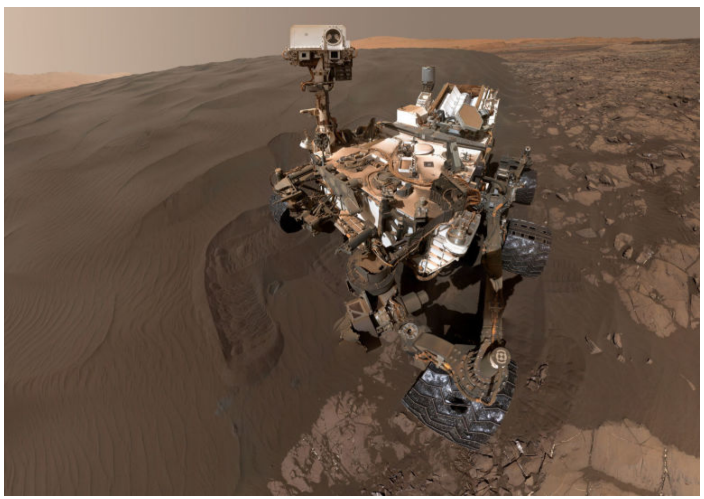
Backup Slides

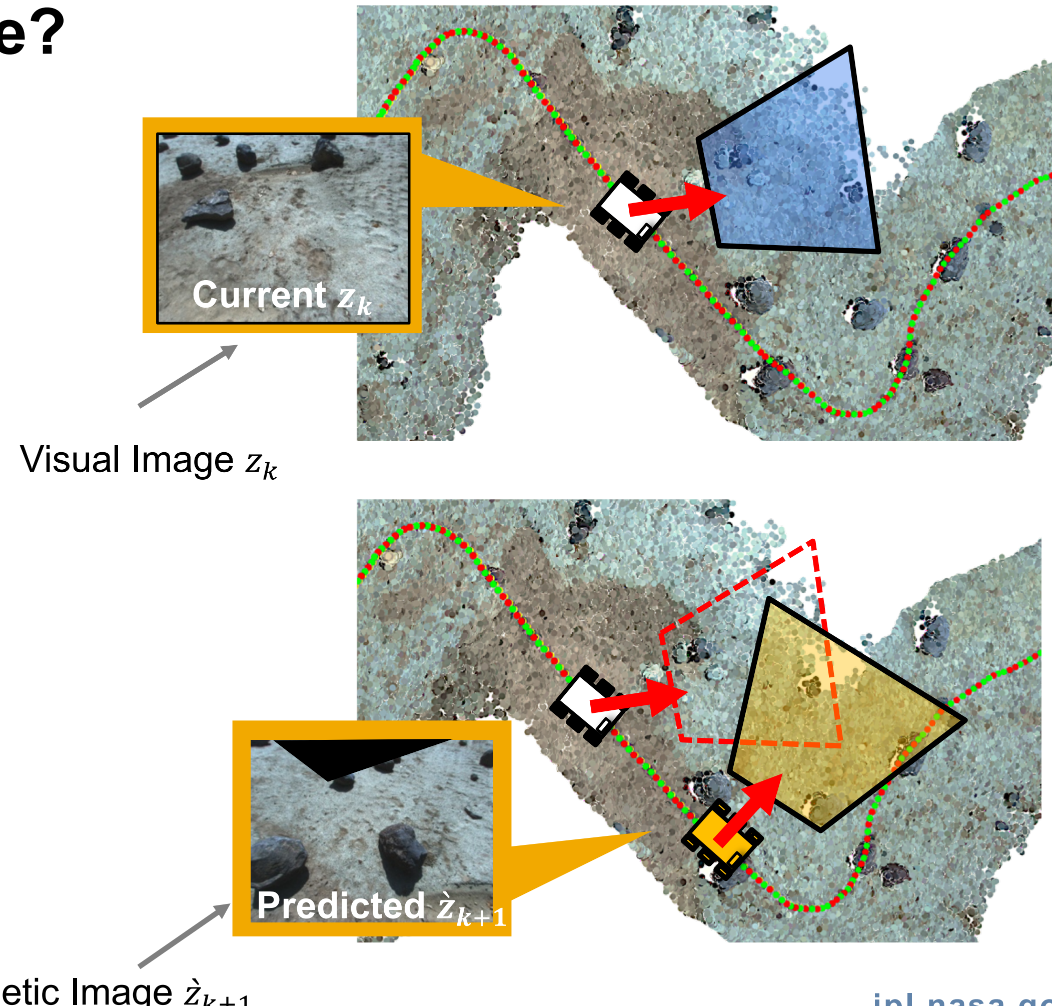
Future Work: Perception-aware Motion Planning

Future image synthesis and performance prediction

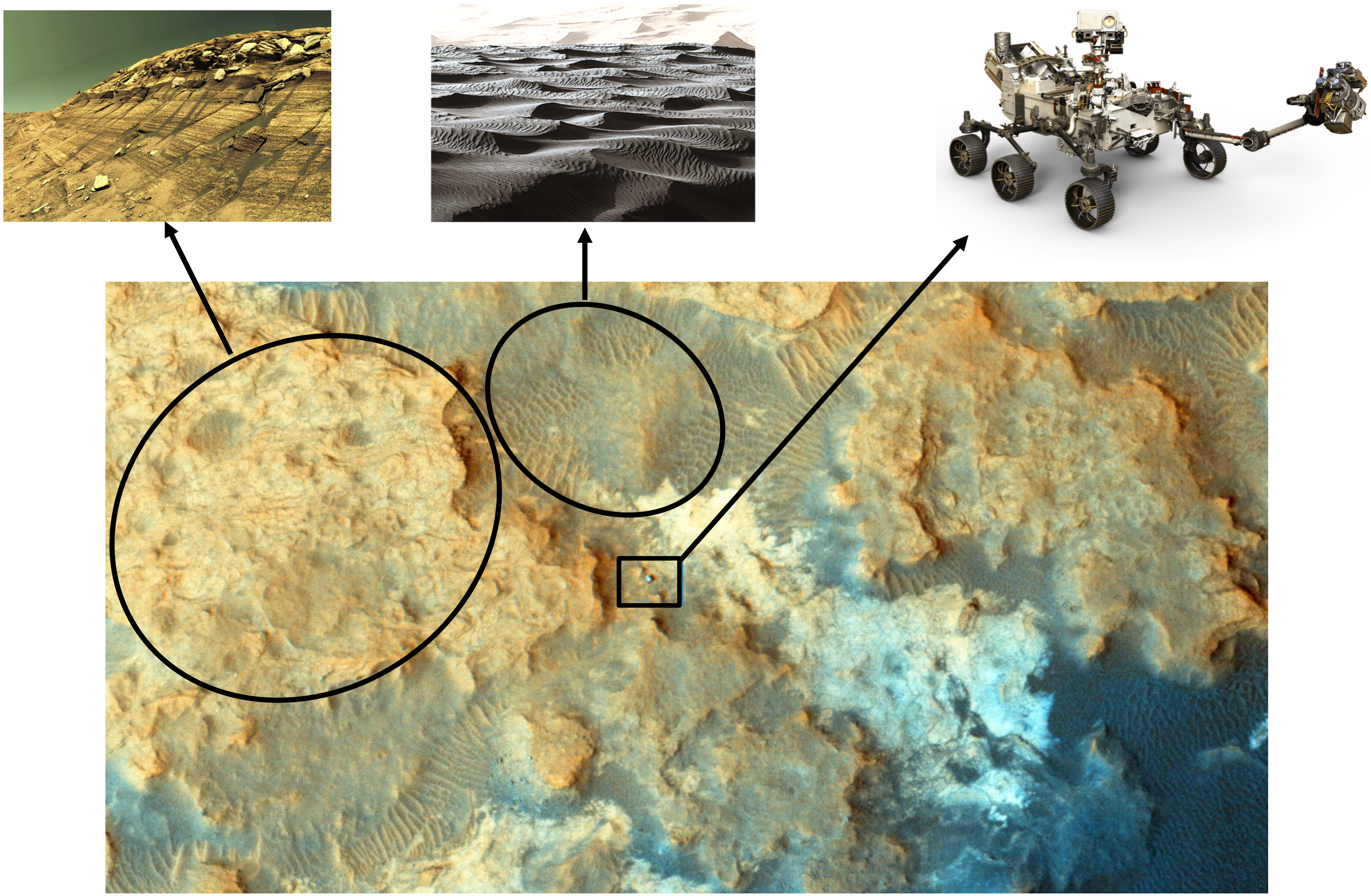
Where **to point mast?**

When **to take image?**





Rover Localization on HiRISE Imagery



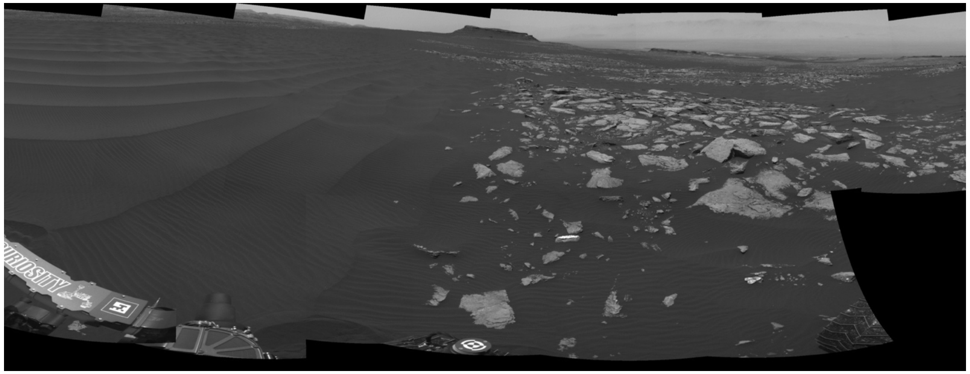
Curiosity rover can be seen at the Pahrump Hills area of Gale Crater in this view from the HiRISE camera on the Mars Reconnaissance Orbiter. Image credit: NASA / JPL-Caltech / University of Arizona.

Summary of Experiments

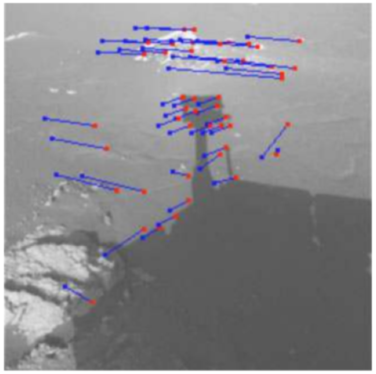
Feasibility, robustness and performance of A2G localization is studied under following conditions:

Experiment	Performance Metric
A2G Viewing Angle Variations	Number of correct matches
Feature detector/descriptor variations	Number of correct matches Localization Error
Illumination Variations	Localization Error
Terrain Type Variations	Localization Error

Autonomous Vision-based Navigation



Feature-poor terrain on Mars
(Left: MSL Curiosity, Right: MER Opportunity)



Feature tracking failure
due to rover shadow

Challenges:

- Failure to detect features on low texture terrain
- Failure to track features due to glare or shadows

Current Solution:

- Human intervention (manual mast pointing)

Alternative Solution:

- perception-aware mast pointing to reduce uncertainty and visual odometry failure